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For the Participant:

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CRADA FINAL REPORT
FOR
CARDA NUMBER ORNL02-0649

High Thermal Conductivity Carbon Foam used for Thermal Management of Engine Oil

Ronald Ott, April McMillan and Ashok Choudhury
Oak Ridge National Laboratory

Bill Anderson and Frances Lockwood
Ashland Incorporated and its Division Valvoline Company

Prepared by the
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
managed by
UT-BATTELLE, LLC
for the
U.S. DEPARTMENT OF ENERGY
Under Contract DE-AC05-00OR22725

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Abstract

The need for maintaining a lower specific engine oil temperature is essential in enhancing the longevity of the oil and of the engine and its components. By decreasing the engine oil temperature the oil is able to perform its job more efficiently. It is proposed to use the carbon foam, with its exceptional thermal management capabilities, to aid in reducing and stabilizing the engine oil temperature during steady state operation. Also, it is possible to use the carbon foam to heat the engine oil during startup to reduce emissions and possibly engine wear.

The mesophase pitch derived carbon foam, developed at Oak Ridge National Laboratory, is a material that offers excellent thermal management capability. The foam has an open cell structure (0.98 fraction open porosity) with graphitic ligaments aligned parallel to the cell walls. The alignment of the graphitic ligaments in a three dimensional array gives the foam homogeneous thermal properties, unlike graphite fibers. The bulk thermal conductivity of the foam has been measured to be 175 W/m·K, placing it on the level of 6061 aluminum, which has a bulk thermal conductivity of 180 W/m·K. Copper has a bulk thermal conductivity over two times higher, at 400 W/m·K.

The proposed research will entail using the carbon foam, with its excellent thermal management capabilities, as a cooling and heating medium for engine oil, or in other words an oil temperature regulator. The foam will aid in maintaining a specific oil temperature during steady state operation and in heating of the engine oil at startup. Being able to maintain a consistent oil temperature will ensure better operation of engine oil, by extending the life of the oil and engine. All Parties will conduct research efforts in order to determine the best utilization of the carbon foam in managing engine oil temperatures.

Statement of Objectives

There are several technological issues associated with the carbon foam that must be addressed in order to determine its compatibility with engine oil. The compatibility must be determined under relevant operating conditions, i.e. oil flow rates, oil operating temperature range, oil viscosity, oil system pressure, to just name a few. The preliminary design of the carbon foam thermal management element will be such that it can be incorporated into the engine oil filter. This will aid in reducing the weight, size, cost and complexity of the engine oil cooling system.

The objectives of this research effort are outlined below.

1. Estimate the engine parameters (SI units) on a 2.3-liter engine (used for benching testing) in order to determine a heat balance.
   - 5 quart oil capacity with oil filter using 5W-30 weight oil
   - Oil flow rate
   - Oil sump temperature
   - Oil temperatures coming into and out of oil filter housing
   - Coolant flow rate

- Coolant temperatures coming into and out of engine block
- Average under hood temperature
- Air flow rate over oil filter housing
- How fast must the oil be heated in order to significantly impact cold start emissions, and possibly wear?

2. Chemical compatibility of foam and engine oil
   - Wetting, or wicking, of foam by oil, with and without pressure
   - Heat transfer characteristics of carbon foam after it has been exposed to 5W-30 weight engine oil. Do the heat transfer characteristics of the foam change due to oil exposure?
3. Design and test bench rig and carbon foam test element
   - Design 5 quart capacity bench rig that will simulate 2.3-liter engine
   - Test operation of bench rig
   - Design and fabricate carbon foam test element to incorporate into bench rig
4. Run bench experiments and iterate carbon foam test element as needed
   - Bench experiments will be run by varying the following parameters:
     - Oil temperature
     - Oil flow rate
     - Oil pressure
     - Air temperature
     - Air flow rate
   - Carbon foam test element will be iterated as needed to optimize bench experiments

Benefits to the Funding DOE Office's Mission

Today's automotive engines have to run hotter in order to meet requirements for better fuel economy and lower emissions. With the incorporation of an oil cooler, similar to that of the cooling water system radiator, oil temperatures can be reduced and operate at an optimal level. In some cases for larger vehicles part of the water cooling system is used for oil cooling. These systems add weight, cost, and complexity to the vehicle.

It is advantageous to maintain a lower more consistent oil temperature because this allows the oil to perform one of its many duties, one of which is carrying soot to the oil filter. Having thermal stability will allow the possibility to run lighter weight oil, which will help improve fuel economy.

When higher levels of Exhaust Gas Recirculation (EGR) are introduced in the next few years, in order to improve emissions, the oil temperatures will increase approximately 20°F. EGR will also introduce more soot into oil, thus decrease oil life, causing oil breakdown. This will cause soot to aggregate, hence producing larger particles causing filtration problems. So it is critical to try and develop a better alternative to engine oil thermal management systems.

A significant amount of emissions are produced at engine startup, due to low operating temperatures. Being able to warm the engine to operating temperatures rapidly can significantly reduce these emissions and help prevent excessive engine wear. The carbon foam is capable of heating the engine oil at startup, and provides cooling once the engine has reached a steady state temperature.

Thus, fuel efficiency can be increased through methods of better oil thermal management achieved by better thermal management materials which allow weight reduction of cooling systems. The carbon foam is an ideal material for this type of application due to its lightweight and high thermal conductivity.

Technical Discussion of Work Performed by All

Valvoline undertook the responsibility of determining and setting the engine parameters at which benching testing would be accomplished. Since Valvoline's bench testing facility utilized a 2.3 liter 4-cylinder engine these parameters were taken as the standard (refer to Table 1). Valvoline also designed and built a bench test rig in order to evaluate the performance of the carbon foam cooling devices. The bench test rig was designed to simulate the 2.3 liter test engine with regard to oil filter, oil flow rate and capacity. This bench test rig was utilized to evaluate the performance of the various iterations of the carbon foam cooling devices.

Table 1. Bench test engine parameters.

PARAMETER	VALUE
Oil flow rate	19-23 lpm (5-6 gpm)
Oil sump temperatures	93-104°C (200-220°F)
Coolant flow rate	~57 lpm (~15 gpm)
Coolant temperature out of engine	85°C (185°F)
Coolant temperature in of engine	74°C (175°F)
Average under-hood temperature	Ambient at start; >oil sump temperature after shutoff
Air flow rate over filter housing	Static

Oak Ridge National Laboratory assumed the role to evaluate the chemical compatibility of the carbon foam as well as the design and fabrication of the carbon foam oil cooling devices. The chemical compatibility of the carbon foam with engine oil was investigated with respect to wetting, wicking and heat transfer characteristics. For these experiments an 5W-30 weight engine oil was utilized.

Carbon foam in several different processing conditions were tested: graphitized non-oxidized, graphitized oxidized, and non-graphitized non-oxidized conditions. The three different conditions were evaluated to determine if graphitizing and/or oxidizing alter the wetting and wicking ability of the carbon foam. For all three conditions the engine oil wetted and was wicked by the carbon foam.

Valvoline designed a built a test stand in order to mimic the temperatures and flow conditions seen in the 2.3 L engine configuration. Refer to Figure #1 for an image of the test stand. The oil was pumped from a sump that held a heater in order to heat the oil. Then the oil was split into two oil filter housings, one to accommodate the carbon foam test elements and the other for direct comparison. Thermocouples were located such that temperatures of the oil sump, inlet to the oil filters and outlet of the oil filters could be recorded. Also the oil flow rate was recordable. A box fan could be located in front of the oil filter housings in order to mimic on-road conditions – to have low air flows as seen under-hood conditions.

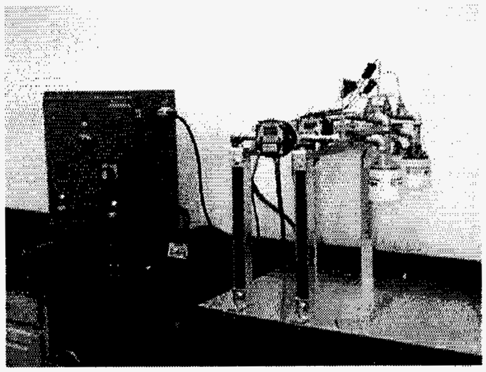

Figure #1. Image of the test stand built at Valvoline.

There were in total 4 iterations of carbon foam design elements. The carbon foam oil cooling element designs 1 through 3 were to be located in conjunction with the oil filter, being located between the oil filter and the oil filter housing. The fourth carbon foam element design was a mockup of a typical aluminum oil cooler.

The first carbon foam design element was a 10" diameter carbon foam disk ½" thick with a copper annulus with an outer diameter of 3" and an inner diameter of 2.25"and a inner carbon foam disk with an outer diameter of 2.25" and an inner diameter of 0.725". The inner carbon foam disk had 8 ¼" holes in order to accommodate the oil flow into and out of the oil filter. Refer to Figure #2 for images of the 10" disk. It was determined that there was not enough surface area at the foam/air interface to remove heat. The carbon foam element was heating but the heat was not able to escape off the surface. Refer to Appendix A for the complete experimental data. It was shown that the lower oil flow rates led to larger heat removal but no where near the amount needed for adequate performance.

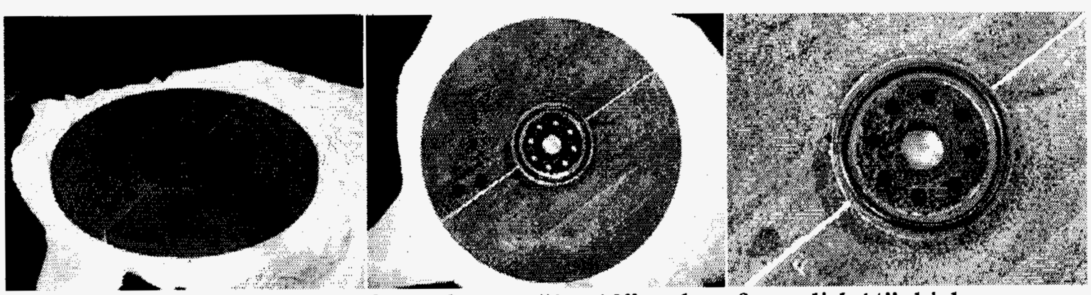

Figure #2. Images of test element #1 – 10" carbon foam disk ½" thick.

In order to increase the surface area on the air side of the foam the second device was fabricated from the first device. The first element was machined down to an outer diameter of 6" and holes where machined radially in order to increase the surface area. Refer to Figure #3 for an ideas of what element #2 looked like – minus the fingers (this is a image of element #3 which is a modification of element #2). The increased surface are on the foam/air side did little to increase the efficiency of the oil cooling carbon foam device. Refer to Appendix B for the experimental data. Again, lower oil flow rates led to larger amounts of heat removal, or inlet outlet temperature variation. From the conclusions of these tests it was decided to increase the foam surface area on the foam/oil side in order to increase the heat transport from the oil to the foam.

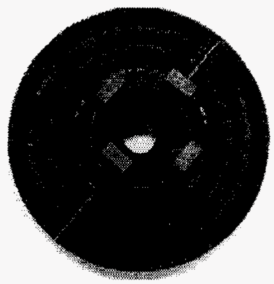

Figure #3. An image of test element #3, but shown here to emphasize the design direction from element #1. Element #2 is simple the disk shown here without the carbon foam fingers.

Test element #3 was test element #2 with carbon foam fingers applied to the foam/oil side in order to increase the surface area. Four 2" carbon foam fingers were inserted into 4 of the ¼" holes within the inner carbon foam disk which would be inserted into the oil filter. Refer to Figure #4 for images of test element #3. The internal portion of the oil filter was removed in order to accommodate the carbon foam fingers. The increased surface area on the foam/oil side failed to increase the device's efficiency in removing heat from the oil stream. Refer to Appendix C for the complete experimental data.

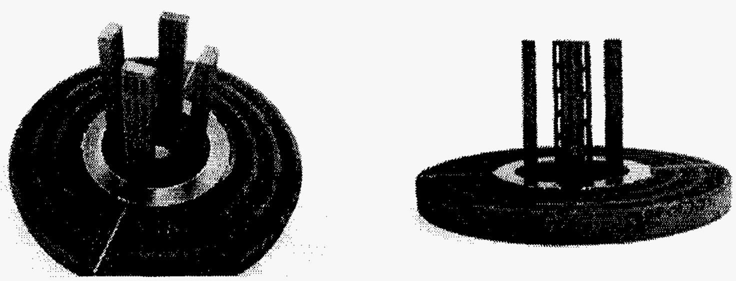

Figure #4. Images of test element #4 showing the insertion of the carbon foam fingers.

Test element #4 was a mockup of a traditional aluminum oil cooler radiator. Dimensions were taken from a NAPA transmission oil cooler part #ATP 1-4823 and this oil cooler was used in side-by-side testing of the carbon foam oil cooler. Although this device performed better at removing heat from the oil it did not perform better than the NAPA reference cooler. The NAPA reference oil cooler out performed the carbon foam mockup oil cooler in all respects. Refer to Figure #5 for an image of element 4 and refer to Appendix D for complete experimental data.

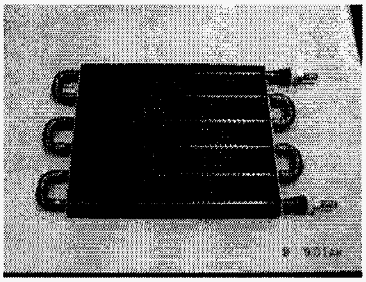

Figure #5. Image of test element #4. Mockup of a typical oil cooler.

Subject Inventions (As defined in the CRADA)

Patent #6,729,269 "Carbon or graphite foam as a heating element and system thereof" was developed by works at ORNL based on discussions and earlier experiments.

Commercialization Possibilities

Due to the lack of performance and cost associated with the carbon foam, no commercialization opportunities are seen in the near future. The technology utilizing carbon foam as an oil cooling medium is too immature at this point and significant research needs to be performed to truly understand its response in such an environment.

Plans for Future Collaboration

Currently, there are no plans for future collaboration.

Conclusions

As designed the carbon foam oil cooling devices did not perform as expected in association with the oil filter or as a stand alone oil cooler. The carbon foam oil cooler performed better at removing heat from the engine oil than the carbon foam test elements designed to be retrofitted with the oil filter and housing. There are many factors that contributed to the lack of performance of the carbon foam oil cooling devices and the main one being the lack of understanding of the heat transfer on the oil/foam side as well as the foam/air side.

Appendix A

	Test filter			Test Element			
Flow Rate (gpm)	Tin (F)	Tout (F)	dT (F)	Tid(F)	Tod (F)	Air	Air speed (fpm)
6.01	194	194	0	161.5	141	80	stag.
6.01	196	196	0	162.1	136	78	stag.
6.01	196	196	0	166	129.2	79	stag.
6.01	194	193	-1	130.2	87	78	2400
6.01	196	195	-1	133.4	93.2	78	2400
6.01	194	193	-1	131.3	92.5	78	2400
3.04	194	193	-1	157.2	98.6	82	stag.
3.04	195	194	-1	157.8	90.9	82	stag.
3.04	197	196	-1	157.4	91.2	82	stag.
3.04	193	191	-2	123.5	99.4	75.6	2000
3.04	193	191	-2	125.1	103.8	75.6	2000
3.04	195	193	-2	125.4	92.8	75.6	2000
0.99	193	192	-1	149.6	135.8	81	stag.
0.99	192	191	-1	150.2	109.8	81	stag.
0.99	195	193	-2	152	110.3	79	stag.
0.99	192	189	-3	116.2	102.9	75.8	2145
0.99	191	188	-3	119.2	88.6	75.8	2145
0.99	192	189	-3	113.1	91	75.8	2145
0.21	186	177	-9			76	2145
0.21	186	176	-10			76	2145

Notes:

Date: February 26, 2003

1 Sump temperature (nominal) = 200 F.
2 Inlet temp of oil filter 2 is same as test filter.
3 No temp. difference was seen on filter 2 at 6 gpm.
4 The temperature difference on filter 2 was 1-2 deg less than that for the test filter at 3 and 1 gpm.
5 The temperature difference on filter 2 appeared to be more than on the test filter at 0.21 gpm.
6 Test element temps are approximate.
7 Stagnant air temp was measured above test element.
8 Fan was placed about 18 inches in fron of filters, and half-way between them.

Appendix B

Flow Rate (gpm)	Test Filter Tin (F)	Test Filter Tout (F)	Test Filter dT (F)	Reference Filter Tin (F)	Reference Filter Tout (F)	Reference Filter dT (F)	Air	Air speed (fpm)
6	196	196	0	196	196	0	80	1000
5	196	194	-2	195	195	0	80	1000
4	196	194	-2	196	195	-1	80	1000
4	196	194	-2	195	194	-1	80	1500
3	198	196	-2	197	196	-1	80	1000
2	197	194	-3	196	194	-2	80	1000
1	193	188	-5	192	189	-3	80	1000
1	195	193	-2	195	194	-1	80	0
6	198	198	0	199	199	0	80	0

Notes:

Date: May 19, 2003

1. Sump temperature (nominal) = 200 F.
2. Stagnant air temp was measured above test elements.
3. Fan was placed about 18 inches in front of filters, and half-way between them.
4. Since no significant temperature changes are seen, future tests are to be cool-down tests.

Appendix C

Cool-Down Test - No air flow

Reference

Time (h)	Tin (F)	Tout (F)	**dT (F)**	Tair (F)	Ts (F)
0	199	199	**0**	84	191
1	174	174	**0**	80	170
2	161	161	**0**	77	156
2.5	157	157	**0**	76	151
3	154	154	**0**	83	150

Test Element

Time (h)	Tin (F)	Tout (F)	**dT (F)**	Tair (F)	Ts (F)
0	197	197	**0**	89	190
0.75	183	183	**0**	88	178
1.75	162	162	**0**	82	158
2.75	154	154	**0**	78	150
3.15	152	152	**0**	77	149

Cool-Down Test - with air flow

Reference

Time (min)	Tin (F)	Tout (F)	**dTin (F)**	Tair (F)	Ts (F)	Air flow (fpm)
0	197	197	**0**	85	190	1800
15	180	179	**-17**	79	177	1800
30	167	166	**-30**	80	165	1800
40	160	159	**-37**	80	157	1800
50	154	153	**-43**	80	151	1800
60	150	149	**-47**	80	146	1800

Test Element

Time (min)	Tin (F)	Tout (F)	**dTin (F)**	Tair (F)	Ts (F)	Air flow (fpm)
0	200	200	**0**	84	194	1800
15	178	177	**-22**	80	175	1800
30	164	163	**-36**	82	161	1800
40	156	155	**-44**	81	153	1800
50	150	149	**-50**	81	147	1800

Procedure

1 Same test rig is used as previously. Oil filters have filter element removed.
2 Heater and pump are turned on for 1 hour.
3 One line is closed and oil is pumped through other.
Oil flow is set at 3
4 gpm.
5 Initial nominal sump temperature (Ts) is set at 200 F.

6 Heat is turned off and cool-down (**dTin**) is recorded.
7 Test element is inserted into line at filter, and steps 1-5 are repeated.

Appendix D

Air speed (fpm)	Flow rate (gpm)	Test Cooler Tin (F)	Tout (F)	**dTt (F)**	Tair (F)	Reference Cooler Tin (F)	Tout (F)	**dTr (F)**	Tair (F)
0	2	194	195	**1**	86	197	195	**-2**	84
0	1.5	193	192	**-1**	87	195	194	**-1**	84
0	1	193	192	**-1**	87	195	193	**-2**	84
0	0.5	194	192	**-2**	87	196	192	**-4**	84
1500	2	194	187	**-7**	85	194	177	**-17**	86
1500	1.5	192	184	**-8**	85	192	172	**-20**	84
1500	1	191	181	**-10**	85	192	166	**-26**	84
1500	0.5	190	175	**-15**	85	191	158	**-33**	84
2500	2	192	186	**-6**	86	192	174	**-18**	84
2500	1.5	193	185	**-8**	86	193	171	**-22**	84
2500	1	190	179	**-11**	86	193	166	**-27**	84
2500	0.5	189	171	**-18**	86	190	158	**-32**	84

Notes: Date: August 10, 2004

1. Same test rig is used as previously with one filter removed and replaced with cooler.
2. Sump temperature (nominal) = 200 F.
3. Air temp was measured 3 inches in front of center of oil coolers.
4. Fan was placed about 18 inches in front of coolers, with a duct directing flow.
5. **Reference cooler is NAPA Transmission Oil Cooler Part # ATP 1-4823**